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Technical Document 2033
February 1991

Evaporation Duct Communication: Test Plan

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ADMINISTRATIVE INFORMATION

This report was prepared under project RC32C11 of the Command Systems Block Program. This block is managed by Naval Ocean Systems Center under the guidance and direction of the Office of Naval Technology. The work was funded under program element 0602232N and was performed by members of Code 543, Naval Ocean Systems Center, San Diego, CA 92152-5000.

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SUMMARY

The evaporation duct communication (EDCOM) project is an effort to provide an alternative ship-to-ship communications channel by properly exploiting the natural environment. It is a unique project in that a microwave communications circuit (similar to the commercial line-of-sight (LOS) microwave links that carry voice and data across the country) will be used on an over-water, over-the-horizon (OTH) path where successful communication is critically dependent on the evaporation duct. A one-way, 83-km transmission path will be instrumented to simultaneously measure surface meteorological conditions and radio frequency (RF) characteristics of the communication channel. Measurements of bit-error rate (BER), made at DS-1 transmission rates of 1.544 megabits per second, will be compared to propagation models that predict BER from knowledge of the surface meteorology. These comparisons will be used to validate or improve the propagation models so that the performance of similar communication circuits can be predicted from knowledge of the environmental conditions.

The EDCOM project has two objectives. First, EDCOM will demonstrate the feasibility of an OTH communications link that depends on the evaporation duct for successful link operation. Second, EDCOM will validate a propagation model that can be confidently used to guide the development and design of an alternative communications link for U.S. Navy ship-to-ship communications.

CONTENTS

FIGURES

CONTENTS (continued)

FIGURES (continued)

TABLES

INTRODUCTION

"The most often expressed communications problem in Navy Battle Group (NBG) communications is the lack of channels or bandwidth" (Rockway and James, in press). One technique to reduce the NBG communication problem is to establish a network of links and nodes tying the NBG elements together. If there are multiple links to a node, then the bandwidth increases and, particularly in a stressed situation, there is a greater probability of at least one operational link. Essentially, the more alternative communication channels there are between nodes, the higher the probability of successful communication.

A recent study by Rockway and James (in press) of alternative NBG communication channels indicates that the oceanic evaporation duct could be used to support line of sight (LOS) as well as over-the-horizon (OTH) ship-to-ship communications. The authors examined three frequencies (4.5, 9.0, and 18.0 GHz) and concluded that 9.0 GHz is the optimum choice for typical ship-to-ship communications at ranges between 50 and 100 km. Their link budgets indicate that data rates of tens to hundreds of megabits per second (Mb/s) are possible even at these OTH ranges. This potential link performance may be of great value to NBG communications.

Rockway and James recommend starting a program to evaluate the performance of a microwave communications link that could be designed to use the evaporation duct as a communications channel. They propose four tasks: (1) system engineering, (2) network engineering, (3) radio frequency (RF) engineering, and (4) experimental evaluation of the concept. System engineering determines the requirements and evaluates the costs. Network engineering determines the link and node topology and protocols. RF engineering implements the radio links to meet system and network requirements. The experimental evaluation provides measurements of the communication channel that can be used as guidelines in the system, network, and RF engineering tasks. This paper addresses the experimental evaluation task known as the Evaporation Duct Communications (EDCOM) effort.

An evaporation duct can support RF propagation to ranges well beyond the normal radio horizon. Numerous investigators have examined the phenomenon of evaporation ducting and its effects on propagation at frequencies from 600 MHz to 94 GHz (Jeske, 1965; Katzin, Bauchman, and Binnian, 1947; Richter and Hitney, 1988; Anderson, 1982; Anderson, 1990; and Hitney and Veith, 1990). The results of these efforts, primarily one-way continuous wave (cw) and radar measurements, have been used to develop and refine numerical propagation models (Baumgartner, 1983; Dockery and Thews, 1989; and Ryan, 1989) and to spur the creation of a global evaporation duct climatology (Patterson, 1982).

Current state-of-the-art propagation models reliably predict the average received signal level (ARSL), where the average is computed over observation periods on the order of hours or days. Instantaneous received signal level (IRSL) contains signal fluctuations on the order of seconds or minutes and is not adequately modeled. Modeling accuracy is not limited by the physics of the models but rather by the accuracy in physical measurements of the environmental conditions along the path.

In practice, surface meteorology is measured at one or both terminal sites, and these measurements are used to represent the entire propagation path. Therefore, ARSL time scales are commensurate with mesoscale meteorology; usually on the order of hours. Strongly affected by spatial and temporal variations of the meteorological conditions along the path, IRSL affects the bit-error rate (BER) and the overall reliability of the communications circuit. IRSL is associated with microscale meteorological effects that are extremely difficult to measure on a moderate length path.

Current propagation modeling results clearly indicate that the ARSL is sufficient to obtain 50- to 90-percent reliability with a communication link. The major question that EDCOM must answer is whether or not the IRSL is sufficient for reliable communications.

The remainder of the report will examine the evaporation duct and the RF propagation models as well as propose hardware to instrument a test link. The intent is to provide an overview; details of the evaporation duct and propagation models are available elsewhere in the literature. The experimental setup is reviewed based on conversations with equipment manufacturers as to what equipment is available as well as results from the ducting and propagation models.

MODELS

EVAPORATION DUCT

The evaporation duct is a nearly permanent propagation mechanism created by a rapid decrease of moisture immediately above the ocean surface. Air adjacent to the surface is saturated with water vapor and rapidly dries out with increasing height until an ambient value of water vapor content is reached, which is dependent on general meteorological conditions. The negative water vapor pressure gradient just above the surface causes a negative modified refractivity gradient, which creates a surface duct. The height where the modified refractivity reaches a minimum is defined as the evaporation duct height and is a measure of the strength of the duct. Typical duct heights range from a few meters to approximately 20 m; the average evaporation duct height is 13.6 m (Patterson, 1982). Strong trapping is rarely observed for frequencies below 2 GHz because these ducts are vertically thin.

In practice, boundary-layer theory relates bulk surface meteorological measurements of air temperature, sea temperature, wind speed, and humidity to the evaporation duct height. In this analysis, evaporation duct height is computed using the Jeske model (1965, 1971) as implemented by Hitney (1975) with thermal stability modifications suggested by Paulus (1985). In a thermally neutral atmosphere, where the air-sea temperature difference is 0, the modified refractivity profile is given by

$$M(z) = M(0) + 0.125 \{z - (\delta + z_o) \, ln \, [(z + z_o)/z_o]\} \tag{1}$$

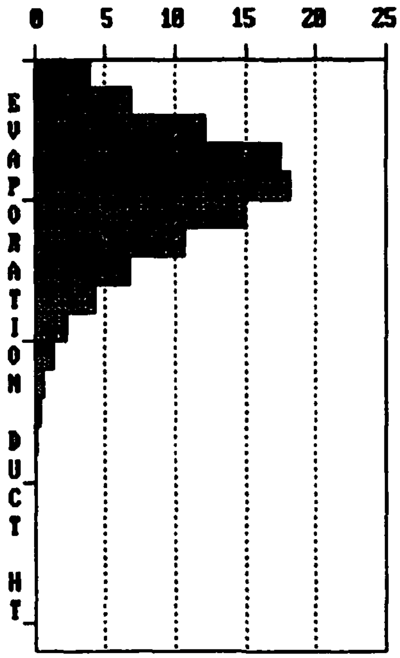
where z is height above the ocean, δ is evaporation duct height, and z_0 is a length characterizing boundary roughness (Paulus, 1985).

Figure 1 shows the distribution of evaporation duct heights for the San Diego offshore area. The distribution is based on 15 years of surface meteorological measurements made by ships operating in the area (Patterson, 1982). Evaporation duct heights of 6 to 12 m are observed approximately half the time; the average duct height is 9 m. Thick ducts, in excess of 24 m, are expected less than 1 percent of the time.

RF PROPAGATION

Numerical propagation modeling techniques agree with RF measurement results when single-station surface meteorological observations are available to determine the refractivity-versus-altitude profile of the evaporation duct (Jeske, 1965; Katzin, Bauchman, and Binnian, 1947; Richter and Hitney, 1988; Anderson, 1982; Anderson, 1990; and Hitney and Veith, 1990). In this study, the evaporation duct is assumed to be (1) range independent and (2) the dominant propagation phenomenon. The effects due to the presence of surface-based and elevated ducts created by advection or subsidence of an air mass are neglected because these ducts are infrequent, occurring only about 10 percent of the time (Patterson, 1982).

EVD HT (m)	% OCCUR
0 to 2	3.9
2 to 4	6.9
4 to 6	12.1
6 to 8	17.4
8 to 10	18.2
10 to 12	14.9
12 to 14	10.6
14 to 16	6.8
16 to 18	4.2
18 to 20	2.3
20 to 22	1.3
22 to 24	0.6
24 to 26	0.4
26 to 28	0.2
28 to 30	0.1
30 to 32	0.1
32 to 34	0.0
34 to 36	0.0
36 to 38	0.0
38 to 40	0.0
> 40	0.0



ANNUAL SURFACE DUCT SUMMARY

SURFACE OBS: MS 120

Latitude:	30 to 40 N
Longitude:	110 to 120 W
Avg EVD height:	9.5 meters
Avg wind speed:	10.5 knots
Sample size:	59,344 observations

Figure 1. Distribution of evaporation duct heights for the San Diego offshore area (Marsden Square 120). Combined day and night averages for all months of the year.

Numerical results are derived using a waveguide formalism (Booker and Walkinshaw, 1946; Budden, 1961; Brekhovskikh, 1970) approach to the analysis of propagation through the troposphere. The computer program used is known as "MLAYER," an enhanced version of the "XWVG" program (Baumgartner, 1983). The program assumes that the vertical profile of refractivity over the sea can be approximated by an arbitrary number of linear segments, and it uses an ingenious technique by Morfitt and Shellman (1976) to find all complex modes that propagate with attenuation rates below a specified value. Surface roughness is developed from Kirchhoff–Huygens theory in terms of rms bump height, which is related to wind speed by the relation $\sigma = 0.0051\, u^2$, where u is wind speed (m/s) (Ament, 1953).

Measurements of the bulk parameters of air temperature, sea temperature, wind speed, and relative humidity are used to calculate the evaporation duct height δ. Equation (1) is used to calculate the vertical refractivity profile needed by the MLAYER program. Measured wind speed is used to calculate the surface roughness parameter, σ, also used by MLAYER.

The results of propagation modeling by MLAYER are expressed in terms of path loss, L, defined as the ratio of power transmitted to power received, assuming loss-free isotropic antennas. Propagation loss (which includes antenna pattern shaping) and path loss are equivalent terms in this analysis because the antenna radiation patterns are known and accounted for in the development. For a one-way transmission system, signal power at the receiver, P_r, is

$$P_r = P_t + G_t - L + G_r \tag{2}$$

where P_t is power transmitted; G_t and G_r are transmitter and receiver antenna gains.

Range dependency of path loss at a frequency of 4.70 GHz is shown in figure 2 for a standard atmosphere (denoted by 0 duct height) and for evaporation duct profiles (neutral stability) corresponding to duct heights of 2 to 24 m. The transmitter and receiver are 25 m above a moderately rough sea surface (wind speed is 7 m/s), and coherent signal propagation is assumed. At a range separation of 80 km, the path loss (L) for transmission through a standard atmosphere is about 215 dB. For propagation in an atmosphere represented by a refractivity profile corresponding to an evaporation duct height of 2 m (a relatively shallow duct), the path loss is approximately 207 dB, a "gain" of 8 dB compared to the diffraction reference. With a 12-m evaporation duct, path loss decreases to approximately 160 dB, a gain of 55 dB. As the duct height increases to 24 m, path loss decreases to 143 dB. If a 24-m evaporation duct exists, received signals are predicted to be 72 dB higher than the level expected under standard atmospheric conditions. Figures 3 and 4, for the same geometry and conditions, show the range dependency of path loss at frequencies of 7.5 and 14.5 GHz.

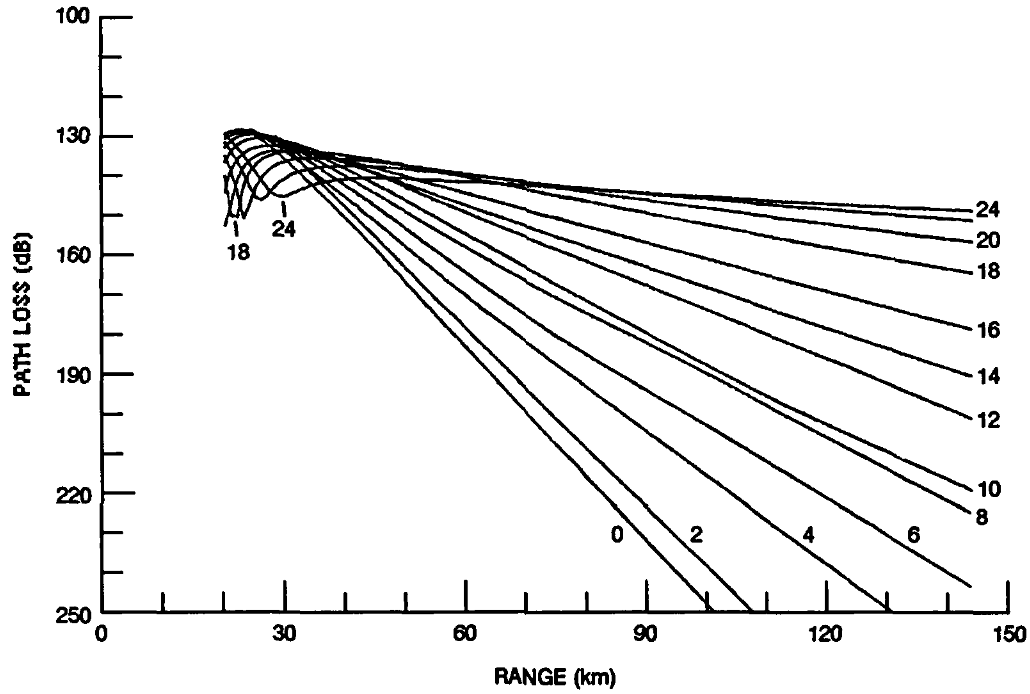


Figure 2. Range dependency of path loss (coherent) for standard atmospheric conditions (labeled as 0 on the plot) and for evaporation duct heights from 2 through 24 m. Frequency is 4.7 GHz. Transmitter and receiver antennas are 25 m above msl.

The plots in figures 2, 3, and 4 illustrate the complicated range dependency of path loss in terms of the evaporation duct and frequency. For 4.7 GHz, at ranges in excess of 70 km, path loss decreases for increasing duct height. For 7.5 GHz, at the same ranges, path loss is a minimum for a duct height of about 18 m; as the duct height increases to 24 m, path loss increases and then decreases with increasing duct height. For 14.5 GHz, path loss decreases with increasing duct height up to about 10 m; as the duct height increases, path loss oscillates between increasing and decreasing. In general, for ranges beyond the horizon (about 40 km), the evaporation duct provides a gain in received signal as compared to the diffraction field reference.

At ranges less than the horizon range, the presence of an evaporation duct may decrease the signal strength as compared to the signal strength expected in a normal atmosphere. In a ray-trace analysis, this effect is due to the increased downward bending of the rays as the duct height increases, which moves the location of the last interference null outward in range.

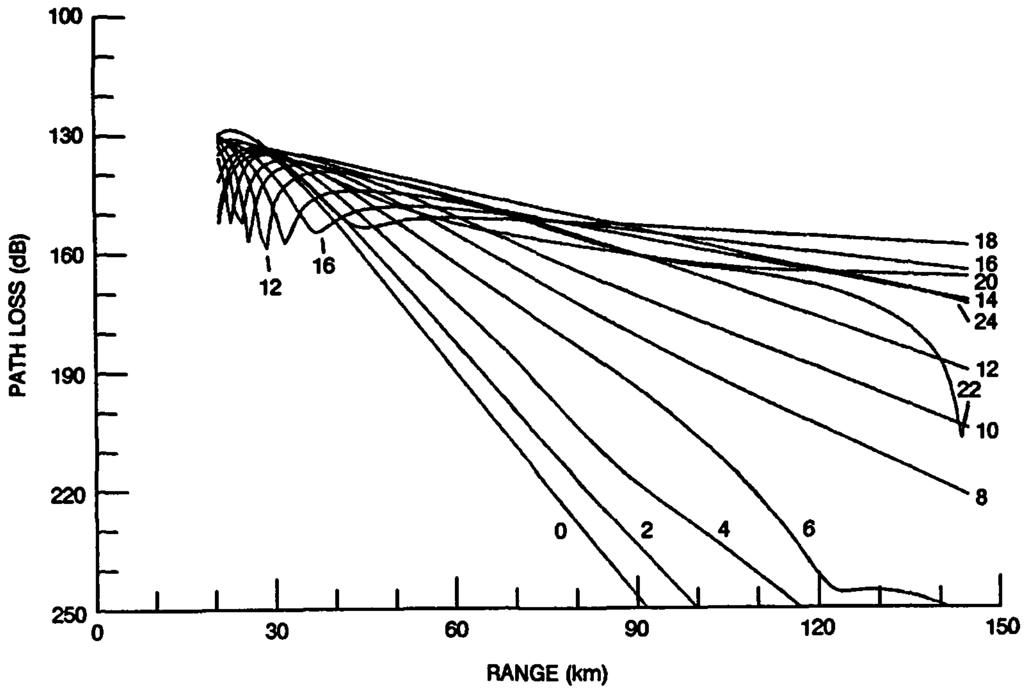


Figure 3. Range dependency of path loss (coherent) for standard atmospheric conditions (labeled as 0 on the plot) and for evaporation duct heights from 2 through 24 m. Frequency is 7.5 GHz. Transmitter and receiver antennas are 25 m above msl.

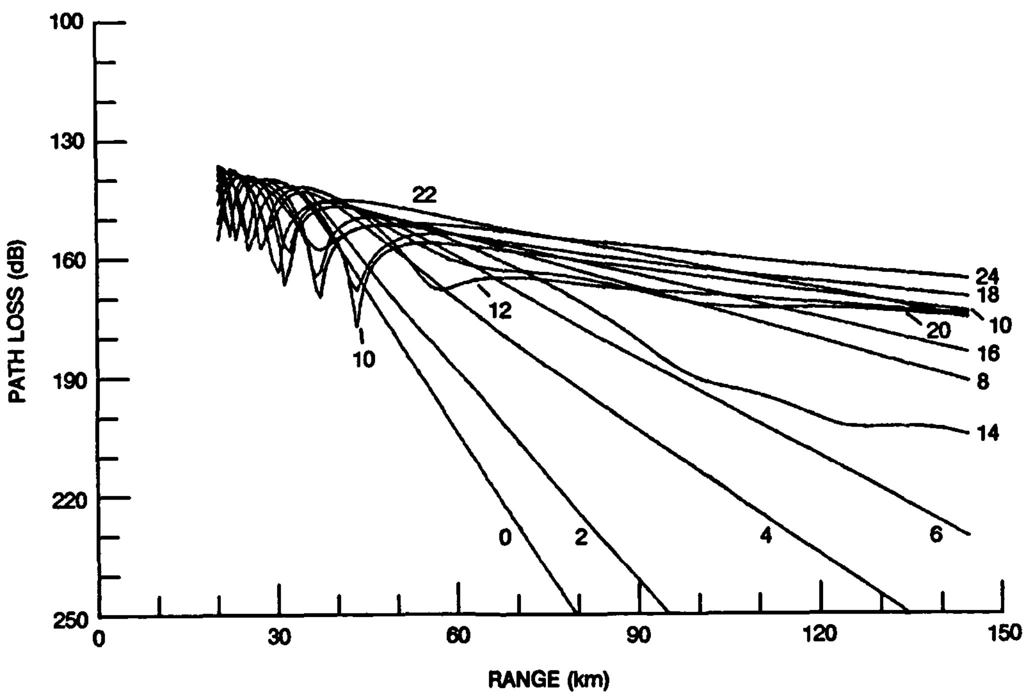


Figure 4. Range dependency of path loss (coherent) for standard atmospheric conditions (labeled as 0 on the plot) and for evaporation duct heights from 2 through 24 m. Frequency is 14.5 GHz. Transmitter and receiver antennas are 25 m above msl.

A systems design for an alternative communication circuit that uses the evaporation duct to achieve OTH communication ranges must consider the effects at all ranges. A complete systems design, as recommended by Rockway and James (in press), should be addressed once the propagation models are validated.

The next section discusses an outline of the proposed experiment, the hardware necessary to implement the measurements, and the expectations of the experimental measurements.

EXPERIMENT DESCRIPTION

OVERVIEW

To provide useful information, the experimental setup will simulate a ship-to-ship communications circuit that might be built. Typical shipboard antenna heights are 25 to 35 m above the ocean surface, which gives radio horizon ranges of 40 to 50 km. Therefore, the path length will be on the order of 50 km. It makes sense to use concepts and equipment that are already being used in the operation of terrestrial LOS microwave links. EDCOM will use commercial digital radio equipment and will validate the propagation models without trying to simulate a complete NBG communications system. Custom RF equipment, necessary to meet NBG systems engineering requirements, is not needed.

A simplex system for one-way data transmission will be established using off-the-shelf equipment. Terrestrial LOS microwave link test equipment has been developed to evaluate channel capacity and reliability. Digital pattern generators and checkers are routinely used to monitor the performance of terrestrial links. This equipment will be used by EDCOM to provide a measure of the link reliability. From the top level, EDCOM will implement a commercial LOS microwave link. The major difference is the path length; EDCOM will use an OTH, over-water path.

PROPAGATION PATH

Placing one terminal at NOSC greatly reduces the costs of monitoring and maintaining the equipment. From NOSC, the practical over-water paths are in the NNW direction, essentially from Oceanside northward. The northern terminal is desirable to be on government property on, or near, the beach and with a clear view to NOSC. Camp Pendleton property extends north from Oceanside to San Clemente. At San Mateo Point, adjacent to the city of San Clemente, the elevation is about 25 m above msl and the view is unobstructed southward to NOSC. Figure 5 shows the proposed propagation path, an 83.1-km over-water path. With the transmitter located 25 m above msl, the radio horizon is 20.6 km and is shown in figure 5 as a dashed arc. The receiver site at NOSC is also at 25 m above msl and has the same radio horizon. Approximately half of the path is blocked by the surface. Figure 6 shows the path profile from San Mateo Point to NOSC; the obstruction is the ocean's surface. Both antennas would have to be situated at a height of 102 m above msl to have an LOS path.

PATH LOSS DISTRIBUTION

Figure 1 shows the distribution of evaporation duct heights as a function of time. For example, duct heights in the interval from 0 to 2 m are expected to occur 4 percent of the time in the San Diego offshore area. The range dependency of path loss at 4.7 GHz in relation to duct height is shown in figure 2. Therefore, for a specified range, one can easily calculate the distribution of path loss as a function of time. From figure 2, the path loss at 4.7 GHz for a 0-m duct height at a range of 83 km is 221 dB; for a 2-m duct height, the path loss is 213 dB at the same range. Therefore, at a range of 83 km, it is expected that path loss in the interval from 213 to 221 dB occurs 4 percent of the time.

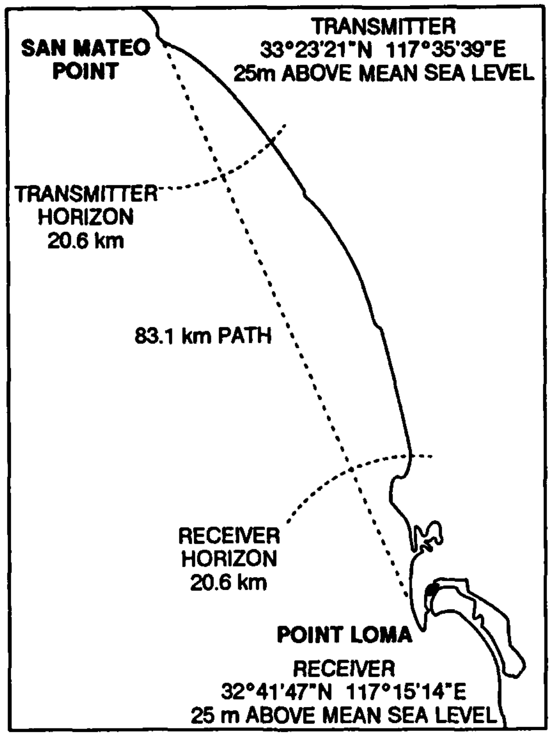


Figure 5. Transmission path from San Mateo Point to NOSC. Path length is 83.1 km. Transmitter and receiver radio horizon shown by dashed arcs.

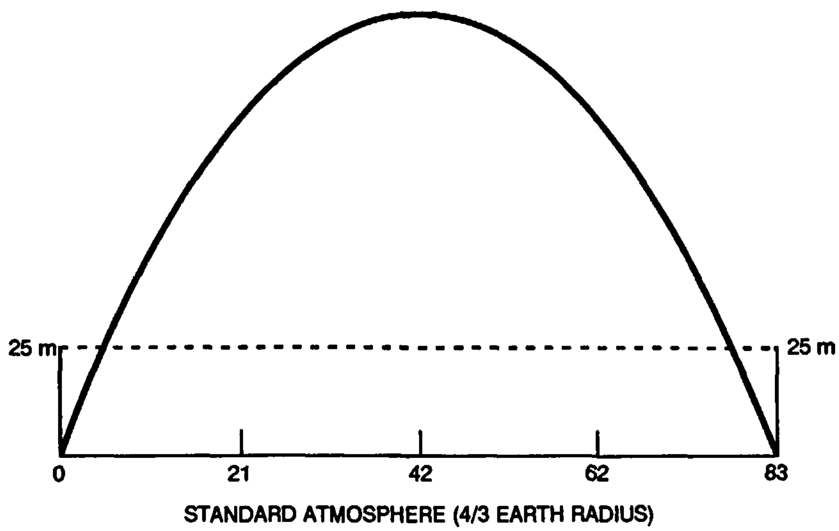


Figure 6. Transmission path profile from San Mateo Point to NOSC. The obstruction is the ocean's surface.

Figure 7 shows the distribution of path loss as a cumulative frequency diagram, where the ordinate indicates the percent of time that values on the abscissa are exceeded. This figure is for the case of a frequency of 4.7 GHz, transmitter and receiver heights at 25 m, and a range separation of 83 km. The diffraction (0-m duct height) and free space (spherical spreading) path loss are indicated by vertical dashed lines. From this figure, path loss is less than 175.5 dB half of the time; 10 percent of the time, path loss exceeds 200 dB (path loss is less than 200 dB 90 percent of the time). Path loss values less than free space are expected a small percentage of the time.

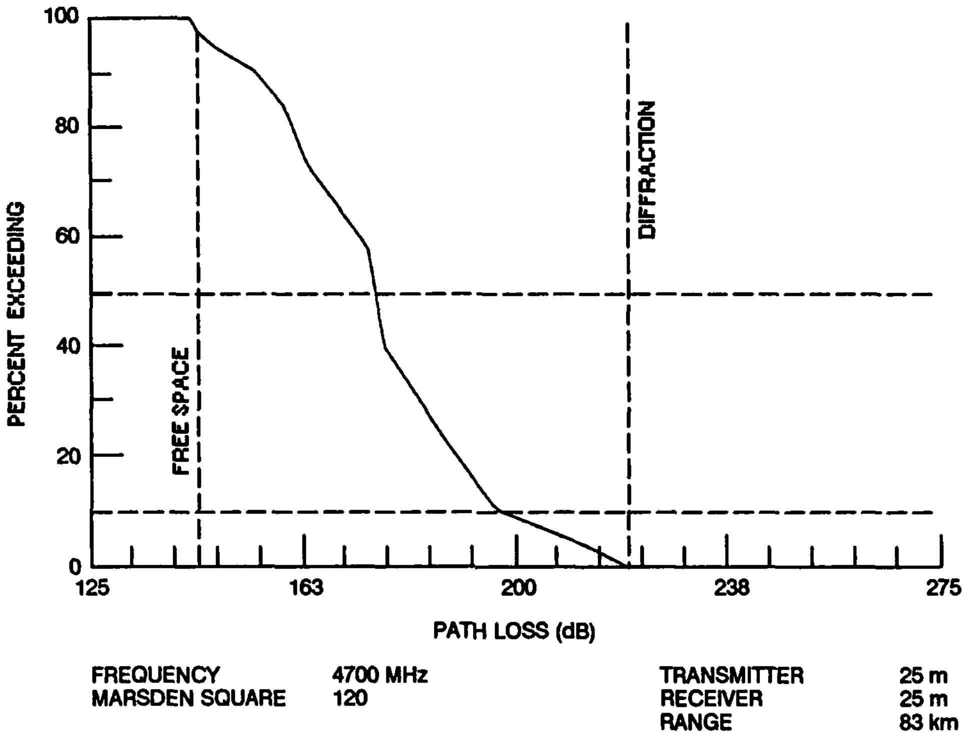


Figure 7. Cumulative frequency distribution of path loss for a transmission frequency of 4.7 GHz. Path is San Mateo Point to NOSC. Free space and diffraction field references are indicated.

The expected distribution of path loss for frequencies of 7.5 and 14.5 GHz are shown in figures 8-9. At 7.5 GHz, the average path loss is 63 dB above the diffraction reference; at 14.5 GHz, the average path loss is 90 dB above diffraction and within 15 dB of free space. As the frequency of transmission increases, so does the system gain provided by the evaporation duct.

DIGITAL RADIO EQUIPMENT

Discussions among the NOSC Frequency Coordinator, the Western Region Frequency Coordinator, and the Navy Frequency Allocation and Assignment Coordinators clearly indicate that the frequency allocation and assignment request should be in the Government frequency bands. Commercial equipment operating in the commercial bands is readily available but there may be frequency conflict with commercial companies. For example, Southern California Edison (SCE) operates a 6-GHz microwave link from the San Onofre power facility to the Encina facility. SCE also operates a 10-GHz link from San Onofre northward. Even though the link from San Mateo Point to NOSC is unlikely to interfere with any other microwave link, there is a possibility of conflict. The discussions with the frequency coordinators indicate that any possibility of interference is grounds for rejection of the frequency allocation and assignment requests. Therefore, it is best to keep the frequencies within the Government bands, which are listed in table 1. The designator "fixed" means these frequencies are applicable for fixed-site transmission.

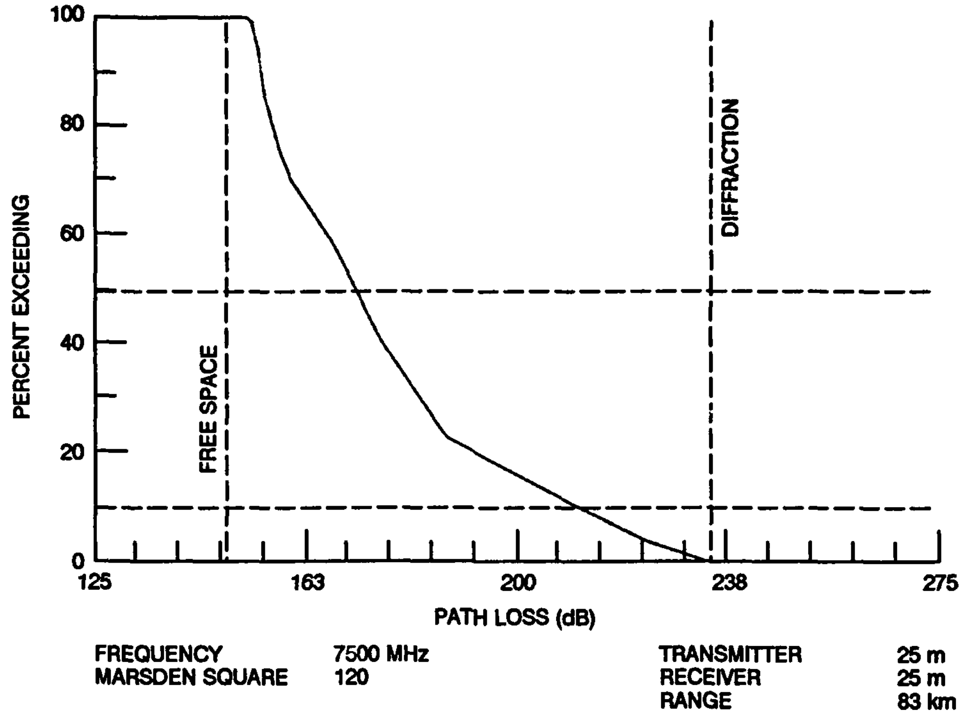


Figure 8. Cumulative frequency distribution of path loss for a transmission frequency of 7.5 GHz. Path is San Mateo Point to NOSC. Free space and diffraction field references are indicated.

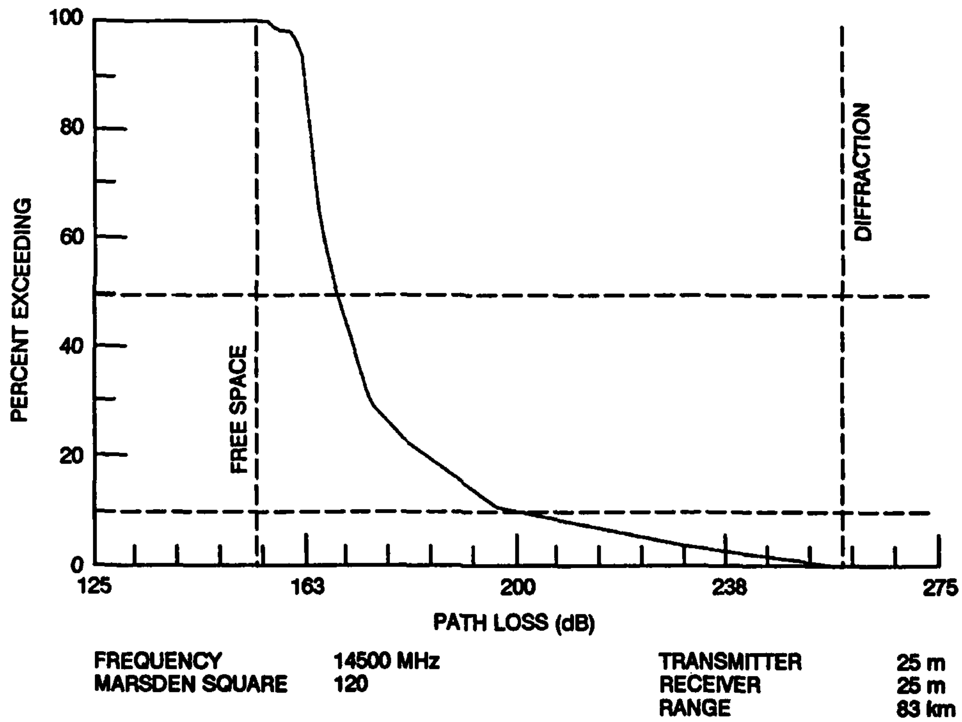


Figure 9. Cumulative frequency distribution of path loss for a transmission frequency of 14.5 GHz. Path is San Mateo Point to NOSC. Free space and diffraction field references are indicated.

Table 1. Applicable government frequencies for fixed-site transmission.

Frequency Range (GHz)			Designator
4.400	–	4.990	Fixed
7.125	–	7.725	Fixed
7.725	–	8.400	Fixed
14.400	–	14.700	Fixed
15.130	–	15.350	Fixed

Discussions with various vendors of digital radio equipment were at times lively. Once the basic path geometry and frequencies were discussed, several sales engineers insisted that a radio link of this nature could not possibly work without repeaters or without considerably raising antenna heights to put the antennas within line-of-sight. A summary of the discussions with the vendors is presented in the following sections.

Northern Telecom, Inc. (NTI)

Contact was made with the digital radio marketing group. NTI promised, several times, to send technical manuals describing the digital radio line for technical review. To date, no documents have been received, even though requests were made several times.

Motorola, Inc.

Motorola's digital radio line is based on their STAR concept — a very capable system, but it does not support the Government frequency bands. A quote was prepared by Motorola for a commercial band system.

Digital Microwave Corporation (DMC)

DMC may have equipment operating in the 7-GHz Government frequency bands. Technical documentation and a quotation were solicited from the company several times. However, to date no quotation for components has been received. Technical documentation consists of one-page line sheets.

Harris/Farinon, Inc.

Harris appears to have equipment in the Government bands and, like DMC, has yet to provide technical documentation or a quotation for equipment. Harris/Farinon, Inc., was contacted several times, and each time a quotation was promised. Technical information consists of one-page line sheets.

Loral, Inc.

Loral has modular radio systems easily configurable that appear to meet all of the requirements. A quotation for components was solicited and received. The cost to implement one link (transmitter and receiver system, simplex) is expected to be about $60K.

TRANSMITTER/RECEIVER SYSTEM

The transmitter/receiver system selected for the EDCOM project is the Loral TerraCom TCM-620 series of digital radios. This equipment is modular and has the inherent form of a simplex transmitter/receiver system. The equipment can handle digital transmission rates from 1.544 Mb/s (DS-1) through 44.736 Mb/s (DS-3). Adequate testing can be done using the DS-1 transmission rate. Additional costs to evaluate the link at higher data rates are not justified at this time. If tests indicate higher data rates need to be evaluated, the hardware can be redesigned to handle DS-2 or DS-3 data rates.

Table 2 lists the power budget parameters for the transmitter/receiver system (DS-1) operating at 4.7, 7.5, and 14.5 GHz. The receiver sensitivity is the minimum received signal power (at the input to the receiver) to maintain a 10^{-6} BER at DS-1 transmission rates. These sensitivities are specified by Loral. From table 2, the transmitter power, antenna gain, and receiver sensitivity (signal power at the receiver) are used to solve eq. 2 for the path loss, L, which is listed as the path loss threshold L_p. There is 0 dB of signal-to-noise ratio, or margin, implicit in the path loss threshold listed in table 2 because the minimum receiver sensitivity has been substituted for received signal power.

For the TCM-622B radio, operating in the 4.4- to 5.0-GHz band, L_p is 185.7 dB. From figure 7, path loss in excess of 185.7 dB is expected to occur 28 percent of the time. Path loss less than 185.7 dB is expected 72 percent of the time. Therefore, with no margin, it is expected that successful communications, or availability, will be achieved 72 percent of the time for the TCM-622B radio link. To obtain commercial availability (99.99 percent or better), requires designing the link to meet or exceed 221-dB L_p; the performance of the TCM-622B radio link would need to be increased by 35 dB. This could be accomplished by increasing the transmitter power from 31.5 dBm (1.4 W) to 66.5 dBm (4.4 kW); however, the costs could be significant. To obtain an availability of 72 percent costs nothing because the evaporation duct provides the system gain. Recognizing the contributions of evaporation ducting to increasing link availability is a crucial step in the design of an alternative NBG communications channel.

Table 2. Loral TerraCom transmitter/receiver specifications and power budget estimates.

Model Number:	TCM-622B	TCM-624A	TCM-628B
Tuneable Frequency (MHz)	4400–5000	7125–7725	14400–15250
Transmitter Power (W [dBm])	1.41 [31.5]	0.66 [28.2]	0.20 [23.0]
Antenna Diameter (m)	1.22	1.22	1.22
Antenna Gain (dBi)	32.6	37.0	42.7
Receiver Noise Figure (dB) (with preselector)	5.5	6.0	8.0
Receiver Sensitivity (dBm) @ 10^{-6} BER (DS-1)	–89.0	–88.5	–86.5
Path Loss Threshold (dBm) @ 0 dB margin	185.7	190.7	194.9

Table 3 lists the expected availability for the three radio links (4.7, 7.5, and 14.5 GHz) in relation to system margins of 0, 10, and 20 dB. The system margin is a design factor accounting for unknown losses, such as rapid fades, that may occur in link operation. The margin is derived by decreasing the L_p value listed in table 2 by the amount of the margin.

Table 3. Expected availability of the EDCOM links.

Frequency (MHz)	4700.0	7500.0	14500.0
0-dB margin	72%	79%	88%
10-dB margin	45%	67%	81%
20-dB margin	28%	48%	71%

Antennas are 25 m above msl. Path length is 83 km. Digital radio specifications are from Table 2. Evaporation duct effects are from figures 7-9.

Allowing a 20-dB margin, the expected availability is 28 percent at 4.7 GHz, 48 percent at 7.5 GHz, and 71 percent at 14.5 GHz. These availabilities can be achieved using commercial, off-the-shelf, equipment. It is expected that a complete systems design for a NBG alternative communications circuit could give availabilities of about 80 to 90 percent at the higher frequencies considered. For example, the antenna gain could be decreased by about 5 dB to increase the horizontal beamwidth, and the radiated power could be increased by 20 dB (from 0.2W to 20W at 14.5 GHz). This gives a 15-dB increase in performance over the commercial systems described in table 2, which implies that an L_p of 200 dB could be obtained at 14.5 GHz with a 20-dB fade margin. The availability is better than 90 percent for a feasible NBG system.

To validate the propagation models, EDCOM needs to be able to provide measurements that can be compared to predictions. The calculations clearly show that commercial equipment can be used to obtain useful information. It is desirable to test the model predictions at two frequencies. Scientifically, validation of the propagation model at two frequencies will provide confidence in the predictions. Also, it is possible that frequency diversity could be effectively used in the operation of an NBG alternative communications link (Hitney and Hitney, 1990).

From tables 2 and 3, it is recommended that the 7.5- and the 14.5-GHz systems be the basis for the EDCOM model validation effort. The higher frequencies are likely candidates for a real NBG systems design and should be included in the EDCOM measurement program to provide confidence to the design engineers.

BER MEASUREMENTS

Terrestrial LOS microwave link test equipment is extensively used to evaluate the reliability of existing links. The Tau-Tron model 5108 is an industry-recognized, versatile DS-1 test instrument. It can generate and receive framed or unframed data patterns and perform more than 60 measurements simultaneously. Table 4 lists some of its pertinent measurements. It is capable of computer control via a RS-232 serial line. This attribute is important because the EDCOM experiment is to be run 24 hours a day, 7 days a week. Computer control is mandatory for collecting and managing the data.

Table 4. Measurement capabilities of the Tau-Tron Model 5108 DS-1 test set (partial list).

Frame Errors and Alarms	Pattern Errors
Total	Total
Average Bit-Error Ratio	Average and Current BER
Out of frame seconds	Errored seconds
Loss of frame events	Severely errored seconds
Loss of frame seconds	Pattern loss seconds
CRC-6 Errors	**G.821 Calculations**
Errored seconds	Unavailable seconds
Severely errored seconds	Errored seconds
% Error-free seconds	Severely errored seconds
Synchronous errored seconds	Degraded minutes

Figure 10 illustrates the EDCOM experiment hardware configuration. Two Tau-Tron 5108 units will be used as DS-1 data pattern generators. The output of each Tau-Tron generator, alternate mark inversion (AMI) line code at 1.544 Mb/s (T1), will feed the input of the Loral digital transmitters. A microcomputer will monitor the operation of the transmitter site to control events and report unusual conditions.

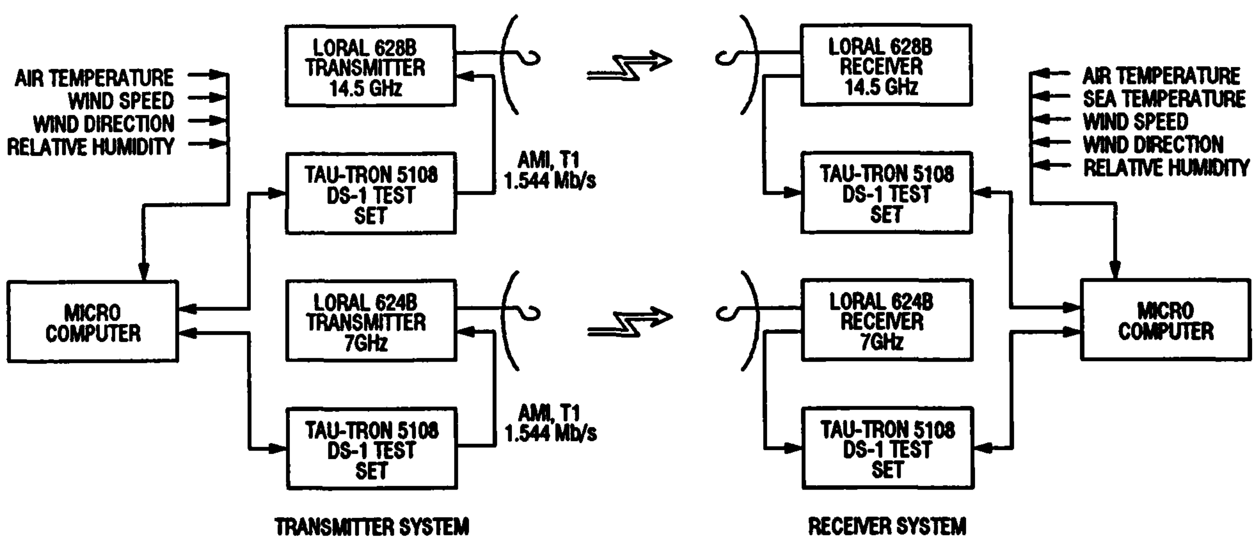


Figure 10. Conceptual diagram of the EDCOM hardware. Transmitter is located at San Mateo Point, CA. Receiver is located at NOSC, Point Loma.

At the receiver site (NOSC), two Tau-Tron 5108s will be used. One connected to the DS-1 output from each of the two Loral receivers. These two units will monitor the DS-1 pattern stream and report the status to a microcomputer that will monitor and control events at the receiver site.

Standard report formats will be established to enable near-realtime analysis of the propagation path. The data will be compared to prediction of propagation characteristics for validation of the numerical models.

METEOROLOGICAL MEASUREMENTS

Measurements of surface sea temperature, air temperature, wind speed, and relative humidity are needed to calculate the evaporation duct refractivity profile. Table 5 lists characteristics of meteorological equipment that have been previously used to calculate evaporation duct profiles and that are proposed to satisfy EDCOM requirements. Wind direction, although not needed for the δ calculations, is a recommended measurement to establish the general wind flow. If the flow is from the east, continental conditions would likely dominate the propagation path and would likely create a surface duct from elevated layers, which will dominate the evaporation duct effects on signal propagation.

Table 5. Characteristics of surface meteorological sensors proposed for EDCOM.

Sensor	Type	Accuracy
Air temperature	Thermistor	0.1°C
Sea temperature	IR Probe	0.1°C
Wind speed	Cup	1%
Wind direction	Vane	1 degree
Relative humidity	Crystallite fiber	6%

These meteorological measurements are recommended to be made at both the transmitter and receiver sites. However, measuring sea surface temperatures at San Mateo Point is not practical because the site is approximately 100 m inland from the beach shore break. These sensors will be monitored by the same microcomputers used to control the RF data measurements (see figure 10).

EDCOM TEST MEASUREMENT DESCRIPTION

TRANSMITTER SITE

The microcomputer at the transmitter site controls the two Tau-Tron 5108 DS-1 test sets and controls the processing of the surface meteorological sensors. Refer to figure 10. Measurements of air temperature, wind speed, wind direction, and relative humidity will be sampled every 10 seconds and averaged for 1 minute. This procedure has been used on previous experiments and has been found to be satisfactory. The average meteorological data will be written to a disk file for later processing.

At the beginning of a measurement period, the computer will command each DS-1 test set to generate a specific DS-1 framing format and test pattern. The framing format will be DS-1 SuperFrame ("D4" format) shown on the Tau-Tron as a "DS-1 SF" format. The test pattern will be an industry-standard quasi-random word, a $2^{20} - 1$ pseudorandom binary sequence (PRBS) with a 14-zero constraint. The line code shall be AMI, and the data rate shall be 1.544 Mb/s, which yields a standard T1 transmission format. The Loral transmitters will be interfaced to the Tau-Trons and shall radiate at 7.7 and 14.5 GHz. The signals radiated are independent of each other.

The microcomputer will periodically interrogate each Tau-Tron unit to verify proper operation. Errors will be recorded onto a disk file for later use.

RECEIVER SITE

The receiver microcomputer (see figure 10) controls the recording of the surface meteorological sensors as well as the DS-1 test sets. Air temperature, sea temperature, wind speed, wind direction, and relative humidity will be sampled once every 10 seconds and averaged for a 1-minute interval. The average meteorological data will be written to a disk file for later processing. Evaporation duct height, dependent upon air-sea temperature difference, wind speed, and relative humidity, will also be calculated for 1-minute intervals.

At the beginning of a measurement period, the computer will command each DS-1 test set to generate a DS-1 framing format and test pattern matching the transmitter pattern generators. The framing format will be DS-1 Super Frame ("D4" format) shown on the Tau-Tron as a "DS-1 SF" format. The test pattern will be an industry standard $2^{20} - 1$ PRBS with a 14-zero constraint. In addition, each Tau-Tron unit will be commanded to generate a status report once every hour. This report, which can be processed by the microcomputer, consists of the following information:

- Title, date, and time
- Period start and length
- Unit setup summary
- Total error count, error seconds, severely errored seconds (SES), consecutive SES
- Average BER
- Percentage of error-free seconds

This data will be displayed in realtime and recorded to a disk file for later processing.

The line code shall be AMI, and the data rate shall be 1.544 Mb/s (T1 transmission). The Loral receivers will be interfaced to the Tau-Trons and shall receive the transmitted signals radiated at 7.7 and 14.5 GHz. The T1 data streams are independent of each other.

The microcomputer will periodically interrogate each Tau-Tron unit to verify proper operation. Errors will be recorded onto a disk file for later use.

EXPECTED MEASUREMENT RESULTS

Figure 11 illustrates the expected results from the EDCOM measurement program. The ordinate is the percent of time that abscissa values are exceeded. For example, a BER of 10^{-6} or less is expected 67 percent of the time for the 7-GHz system (see table 3). At 14 GHz, a BER of 10^{-6} or less is expected 81 percent of the time. The exact shape of the probability curves are estimated. An extensive analysis is needed to adequately model the form of the curves.

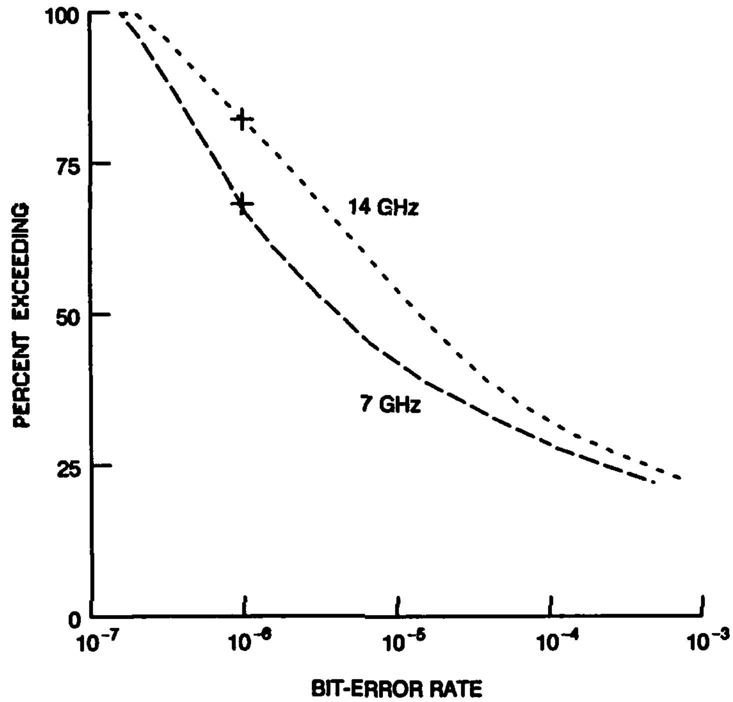


Figure 11. Expected results from the EDCOM measurement program. The probability curves plotted are strictly estimates. The cross at 10^{-6} BER is derived from table 3, 10-dB margin data.

TIME SCHEDULE

All site preparations are expected to be completed by early summer 1991 (July 1991 timeframe). Testing of RF equipment and computer control programs are anticipated to commence upon completion of site preparation and last for several months. It is highly desired to have all testing completed and the link in full operation by September - October 1991.

The following time schedule lists important events that will be met by the EDCOM project.

Table 6. Schedule of EDCOM important events.

	1990			1991									
Event	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Field survey site (NOSC)	>....x												
Develop plans for site	>...........x												
Concrete Slab	>...........x												
Electric Power	>...............x												
Telephone			>.............x										
Field Hut Installation				>...x									
Security Lighting						>........x							
Security Fencing								>.......x					
Test and Integration								>............x					
Full Operations											>..............>		

CONCLUSION AND RECOMMENDATION

Results of propagation modeling show that a microwave communication link, operating at a range separation of more than twice the maximum LOS range, could be constructed to achieve an availability of about 80 percent at a transmission frequency of 14.5 GHz. This link would use commercially available RF equipment and represents a unique use of the environment to enhance communications capabilities. Further, operation of this link will provide the first set of measurements of channel capacity where the channel is critically dependent on the existence of an oceanic evaporation duct.

The measurement program discussed in this paper is strongly recommended to be carried out. Measurements of evaporation ducting channel characteristics represent a unique opportunity to study and evaluate an alternative communications channel that can possibly be used to alleviate NBG communications problems.

GLOSSARY

AMI	alternate mark inversion	LOS	line of sight
ARSL	average received signal level	m	meter
BER	bit-error rate	Mb/s	megabits per second
cw	continuous wave	MHz	megahertz
dB	decibels	m/s	meters per second

dBi	decibel over isotropic	msl	mean sea level
dBm	decibel referred to 1 milliwatt	NBG	Naval battle group
EVD	evaporation duct	NOSC	Naval Ocean Systems Center
EDCOM	evaporation duct communication	OTH	over the horizon
GHz	gigahertz	PRBS	pseudorandom binary sequence
ht	height	RF	radio frequency
IRSL	instantaneous received signal level	SCE	Southern California Edison
km	kilometer	W	watt
kw	kilowatt	SES	severely errored seconds

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 1991	Final: October 1989 — 1990

4. TITLE AND SUBTITLE

EVAPORATION DUCT COMMUNICATION: TEST PLAN

5. FUNDING NUMBERS

PE: 0602232N
PROJ: RC 32C11
SUBPROJ: 84-CHB5-06
ACC: DN300107

6. AUTHOR(S)

K. D. Anderson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Ocean Systems Center
San Diego, CA 92152–5000

8. PERFORMING ORGANIZATION REPORT NUMBER

NOSC TD 2033

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Ocean Systems Center
San Diego, CA 92152–5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Evaporation Duct Communication (EDCOM) project is an effort to provide an alternative ship-to-ship communications channel using the natural environment. A microwave communication link can be used on an over-the-water, over-the-horizon path through the evaporation duct.

This report shows how a microwave communication link, operating at a range separation of more than twice the line-of-sight range, can be constructed. This link can achieve about 80-percent availability at a transmission frequency of 14.5 GHz and can be constructed using off-the-shelf RF equipment. Operation of this link will provide the first set of measurements of channel capacity that can be critically dependent on the existence of an oceanic evaporation duct. Construction of this link presents a unique opportunity to study and evaluate an alternative communications channel that can be used to alleviate naval battlegroup communications load.

14. SUBJECT TERMS

evaporation duct communication
path loss
duct height
propagation path
microwave link

15. NUMBER OF PAGES

27

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

INITIAL DISTRIBUTICN

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